National Aeronautics and Space Administration

2010 PEM Standard
Final Report

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1.0 SPACE PEM STANDARD

Plastic-Encapsulated Microelectronics (PEMs) are not generally recommended for high reliability space missions. However, due mostly to unique technology not available in hermetic military packaging, they are frequently used even in long-duration missions where risk tolerance is small.

PEMs have several failure mechanisms that are non-existent or minimal for devices in traditional hermetic military packages. These microelectronic devices are screened and qualified using traditional procedures as documented in MIL-STD-883, for example. For each PEM failure mechanism discussed herein, the detailed failure modes are explored. A series of risk mitigations are then proposed and evaluated for amount of risk mitigation, cost effectiveness, and simplicity or ease of implementation.

This series of risk mitigations then become the recommended space screening and qualification standard for this PEM. The standard, although similar for many PEMs, is dependent on the details of the wafer and packaging procedures and control techniques. Developing a standard independent of these procedures and controls will not result in an optimal screening and qualification test sequence.

The first steps to be followed in qualifying a PEM for space are an intense discussion and exploration of available data with the part manufacturer (particularly the part manufacturer quality organization). Significant differences typically exist between processes and controls of quality organizations of different part manufacturers, even if the devices are similar in general technology.

The following differences generically exist between traditional high-quality, space-qualified microelectronics and commercial PEMs:

1. Space-qualified microelectronic devices are traceable to the wafer lot and package lot.
2. PEMs are usually tightly controlled in repeatable large-volume manufacturing operations, which are further controlled via in-line and statistical process controls to reduce variation.
3. Space-qualified microelectronics are designed and manufactured with the space environment in mind, e.g., vacuum, unattended low failure rate usage, significant radiation environment (total ionizing dose [TID], single-event effect [SEE], among others).
4. PEMs are not made with the low-volume space environment in mind as a requirement. Instead, PEMs are made for high-volume, highly repeatable applications. Radiation hardness is not a consideration (the space user is entirely responsible to mitigate this risk). Electrical characteristics and limits are chosen to allow a large margin so that failures are very infrequent or nonexistent.
5. PEM wafer design may change. Most PEM manufacturers follow a Product Change Notification (PCN) process.

After discussion with the PEM manufacturer and based on detailed knowledge of the internal manufacturing flows for the actual technology used in the flight parts, the failure mechanism concerns and threats should be ordered as to consequence and probability. Risk mitigations fall into two categories:

1. 100% tests on flight lot parts. Clearly, these would pertain to the highest risks or those risks where even a very low rate of failures is unacceptable for the space mission. These would represent the 100% screening tests.
2. Sample tests on the flight lot. These would represent the qualification tests and include either the not-as-critical characteristics or those that must be evaluated with destructive tests.

Failure mechanisms broadly fall into two categories: fabrication of the active element (or wafer fabrication) and fabrication of the package or interconnect elements. The threat matrix that should be coordinated with the part manufacturer therefore has two matrices (Tables 1-1 and 1-2).

Table 1-1. Wafer Fabrication Significant Failure Mechanisms

Failure Mechanism Concerns	Impact	Mitigation Comments
Different wafer fabs used to make the dice	Differences in wafer fab's may give unintended differences in die characteristics.	Attempt to obtain PEMs from one wafer fab.
Risky wafer technology may be utilized	Critical reliability concerns may relate to certain wafer processing steps such as a particular oxide thickness or defects.	Determine wafer test structures for the wafer feature of concern and impact of feature on PEM characteristics (may impact details of life test).
Relation of wafers used versus wafers used for similar military grade part	If the wafer design and fabrication techniques are identical to the dice used for the similar military part, then the risks (such as infant mortality and long life reliability) may be understood using test data for the military part.	Obtain life test data results and burn-in test data results if possible.
Degree of wafer lot control and traceability	It may not be possible to correlate wafer manufacturer fabrication source and or wafer date code or lot number to PEM flight lot. This may make it difficult to establish wafer design in flight lot with respect to deliberate Process Change Notifications or wafer design changes. Also fabrication anomalies that have reliability impact may not be traceable to the flight lot (a DPA may help).	Identify wafer pedigree to either die features or marking. Use these to establish flight lot pedigree in coordination with DPA.
Risky wafer technology - wafer test structures and use in statistical process control	Determine process control and results for any wafer test structures.	Choose wafers for flight lot if there are significant changes in wafer test structure results. Wafer test structure results may be available in summary from part manufacturer.
Infant mortality	PEM manufacturer may use infant mortality monitor. Examples include sample burn-in or early life test fallout monitor may give an indication of infant mortality rate that is applicable to the flight lot.	May be used to determine the burn-in duration for the flight lot.
Reliability process monitor (periodic reliability testing)	Failure rate in periodic life test of the same part type or similar technology families may be available.	May be used to quantify the risk of failure in life test or fine-tune the life test sample size.

Table 1-2. Packaging Fabrication Significant Failure Mechanisms

Failure Mechanism Concerns	Impact	Mitigation Comments
More than one packaging facility may be utilized. There may be differences between them.	Varying threats between packaging facilities	Attempt to obtain flight lot from one packaging facility.
Packaging technologies used including all materials, fabrication techniques	Threats are dependent on package materials and material compatibility. Fabrication techniques may vary among different package fabricators.	Attempt to obtain flight lot from one packaging facility. Perform risk mitigation based on materials and fabrication techniques in flight lot.
Statistical process controls or in-line tests may be used by packaging facility for package integrity and robustness	Packaging facility or PEM manufacturer may provide acceptable or significant risk mitigation techniques for known threats in flight lot.	Adjust NASA or subcontractor risk mitigations dependent on assessment of threats and manufacturer risk mitigations.
Material compatibility issues	Threats dependent on internal package material interfaces	Adjust risk mitigations based on actual material interfaces in flight lot.
Material Declarations (Material Data Sheet)	Source for material interfaces	Adjust risk mitigations based on actual material interfaces in flight lot.
Lead termination issues and coatings	Solderability and tin whisker formation threats	Determine risk magnitude and appropriate mitigations. Measurement of lead termination (in coordination with qualification sample DPA) may be appropriate.
Package robustness: voids, cracks	Voids and cracks are exacerbated by temperature coefficient of expansion mismatches and criticality of package discontinuities dependent on package design.	Determine risk magnitude and appropriate mitigations.
Coffin-Manson Equation	Frequently valid acceleration factor (see text)	Used to determine appropriate number of temperature cycles for qualification testing.
Internal heat sink and material compatibility issues	Heat sink improves reliability but adds issues in regard to compatibility between lead frame and epoxy mold compound and fabrication controls.	Determine risk magnitude and appropriate mitigations.
Are all epoxy mold compounds used in packaging the same?	If different epoxies are used in the same package, temperature coefficient of expansion differences may exist or material incompatibilities (chemical).	Determine risk magnitude and appropriate mitigations.
Lead frame composition and controls – same as terminals?	Lead frame incompatibilities with silicon die attach and epoxy mold compound	Tests on terminals may mitigate risk of lead frame incompatibilities with silicon die attach and epoxy mold compound.
Storage requirements and controls	MSL ratings and test techniques	Apply controls to ensure MSL restrictions are followed in factory testing.
Tolerant to vacuum?	Outgassing may be an issue.	Obtain epoxy mold compound composition and assess using NASA guidelines for outgassing; or perform direct measurement.
Soldering	Determine from part manufacturer or packaging supplier any restrictions as to temperature and duration of soldering reflow thermal profile.	Use JEDEC pre-conditioning criteria on qualification test samples (JESD22A113) to verify that parts will withstand anticipated solder reflow conditions and still pass reliability criteria.
Wire bonds: material compatibility issues and statistical process control	Obtain in-line or statistical process controls from packaging supplier that ensure wire bond quality and control is sufficient for space applications.	None.

2.0 RISK MITIGATION QUANTITATIVE DETERMINATION

If the risk mitigation includes a statistical distribution known to a high confidence level, then the choice of testing and risk mitigation sample size is susceptible to a quantitative assessment as described below.

The confidence level of a statistical distribution may be thought of in the following manner: Statistical results will change each time the test is run (no matter how well the test is constructed). If one imagines many parallel universes, the test is done in each one. If the percentage of universes in which the test is positive is counted, then the confidence level for this test is the same number (e.g., 95% means 19/20 universes produce the positive result). Clearly, the confidence level is the same as the risk posture for the space mission. Risk-averse missions correspond to confidence levels of 99%. Routine but medium-duration missions (often described as Type 2 missions) correspond to 90% confidence level. High-risk missions need only an average confidence level, which is 60%.

3.0 INFANT MORTALITY DISCUSSION

Since PEMs are generally commercial, industrial, or avionic (temperature range) commercial parts without 100% burn-in, the concern for infant mortality arises. There is controversy between part manufacturers, who often assert that infant mortality is removed by design or process control during the new part development process, and the space community, which wants to see copious flight-lot test data to justify and quantify infant mortality risk.

The usual method to quantify infant mortality risk is to perform 100% burn-in of flight parts at some time interval (often 160 hours or 240 hours). Failures are removed from the lot and the lot is rejected for flight usage if the failure rate exceeds either 5% or 10% [1].

If it is assumed that the failure rate is constant (appropriate to the bottom of the bathtub curve), then life test of a sample of the flight lot provides a quantitative measure of the risk of infant mortals being in the burned-in population. The assumption is that after burn-in, the failure rate has reached the constant (exponential) portion of the bathtub curve and therefore any further infant mortals are upper bounded by the failure rate determined from life testing with the formula (see [1], page 55):

$$\lambda \le \frac{X^2_{1-\alpha}(2)/2}{\sum N_i T_i} \tag{1}$$

In this formula, the summation in the denominator goes over all life test data. The numerator is the chi-square distribution with degree of freedom 2 (appropriate to the situation where no failures occur in the life test) and alpha is the confidence level.

If an acceleration factor (such as Arrhenius) is believed valid, this factor multiplies the times (T) and allows life test data accumulated at various stress conditions to be combined.

The upper-bound failure rate is computed from the life test sample size and the confidence level required. This relation is obtained from the assumptions of a normal distribution of failures during a life test and a constant failure rate (if the failure rate is constant the distribution of failures must be normal). Here, the chi-square distribution is applied with α being the confidence level.

The upper bound computed from life test data can be used to compute the probability of failures in a subsequent (repeat) burn-in (the practical definition of removal of all infant mortals). As an example, if the flight lot is 100 pieces and the burn-in time is 160 hours, then the upper bound to ensure that zero failures occurs in burn-in is:

$$\lambda \le \frac{2.3}{100 * 160} = 143.75 \, failures \;\; per \;\; million \;\; hours \tag{2}$$

to 90% confidence.

It is obvious that the true failure rate for typical modern integrated circuits (order of magnitude 10–300 fits where a fit is one failure per billion operating hours) cannot be demonstrated by the small samples available to the space customer for life test. Therefore, the flight-lot failure rate cannot be adequately estimated from the qualification life test sample. A more adequate estimate of the PEM failure rate must use the more copious data available from the PEM manufacturer and also similarity data within a technology.

To generalize Equation 2, if the burn-in time is 160 hours, and the burn-in sample is $N_{B,}$ then the upper-bound failure rate predicted as a result of a burn-in test (with zero failures) is:

$$\lambda \leq \frac{X^2_{1-\alpha}(2)/2}{160 * N_B} \tag{3}$$

To be specific, the burn-in (or flight test) sample selected is 281 pieces and the required confidence level is 90.0%. The required failure rate to ensure there are zero failures in the burn-in (under these conditions) is 512 per million hours. This seems a reasonable criterion for a space mission and is used in Equation 4.

One may compute an upper-bound failure rate from life test data. The number of device hours in the life test must be (from Equation 1):

$$NT \geq \frac{X^2{}_{1-\alpha}(2)/2}{\lambda_{obj}} \tag{4}$$

Life test sample size required to obtain confidence level that infant mortality has been removed (e.g., another burn-in would result in zero failures) is shown in Table 3-1.

Traditionally, a Level 2 project has required 90% confidence level. Using the same basic assumption (45 pieces for 1,000 hours in life test), a Level 3 project should have 60% confidence level and a Level 1 project should have 99% confidence level.

Table 3-1. Life Test Sample Size

Confidence Level in Percent	Confidence Level	Sample Size
50%	0.5	14
60%	0.6	18
70%	0.7	23
75%	0.75	27
80%	0.8	31
85%	0.85	37
90%	0.9	45
95%	0.95	58
99%	0.99	90
99.5%	0.995	103
99.9%	0.999	135

4.0 PACKAGING AND INTERCONNECT ISSUES

4.1 Generic Packaging Issues

Generic packaging issues are delineated in Table 1-2.

4.2 Package Evaluation/Qualification Testing (e.g., Extended Temperature Cycling)

The root cause of the preponderance of failure mechanisms in almost every plastic package is a significant coefficient of temperature expansion (CTE) mismatch between the package "skeleton" lead frame, the silicon die, the silicon die attach (to the lead frame), the bond wires (and the silicon bond pads), and the epoxy mold compound. The epoxy mold compound (which is really a mixture) has a CTE of approximately 14–15 parts per million per degree Celsius, which is the most different to the CTE of bond wires (typically 17), silicon (close to 3) and lead frame (for alloy 42, this is 4–5). Not unexpectedly, the silicon may separate from the epoxy mold compound with extended temperature cycling. The other material interfaces may also separate but not as much.

Analysis of the CTE mismatches proceeds by using [2] and [3], which state that Coffin-Manson equation is a valid acceleration factor for the brittle epoxy mold compound (e.g. plastic) parts with the formula:

$$DF \approx (T_u - T_l)^k \tag{5}$$

In this formula, the damage factor (DF) is the cracking or void propagation, the two temperatures are the upper and lower temperature of the extended temperature cycling, and k is the Coffin-Manson coefficient. For plastic parts, this is quoted as 6 to 9 (higher number for more brittle epoxy mold compounds). In the remainder of this discussion, 6 is used. Therefore, if a plastic package is subjected to extended temperature cycling at two different upper and lower temperatures, the acceleration factor is:

$$AF = \left[\frac{T_{u1} - T_{l1}}{T_{u2} - T_{l2}} \right]^k \tag{6}$$

Therefore, the mission environment temperature cycling range may be compared to the typical plastic parts qualification range (which is −55 to +125 degrees Celsius) and the mission number of temperature cycles be made into a corresponding number of temperature of cycles for the part qualification testing.

The basic physical failure mechanism of brittle material temperature cycling implies a cumulative damage process. Therefore, the appropriate probability distribution *ab initio* is log normal with a shape parameter greater than 1 (appropriate to wear out failure mechanisms). The failure rate increases with time (or number of cycles in this case). Temperature cycling data from part manufacturers is consistent with this obvious physical mechanism in that failures occur only at a high number of cycles and increases as the number of cycles is increased. This precludes the use of temperature cycling as a screening technique, in that after temperature cycling the parts have an increased failure rate with additional temperature cycles (unlike the case with the more familiar situation of burn-in for operation time).

Since the log normal distribution function is simply a normal distribution of the natural logarithm of the number of temperature cycles (in this case), the sample size required for confidence levels is basically the same. These would be above 90 pieces for 99% confidence level, above 45 pieces for 90% confidence level, and above 18 pieces for 60% confidence level. Due to very regular construction techniques and processes, many plastic packages should have the same distribution function, including mean and standard deviation (which is the shape parameter for the log normal distribution). For example, for an integrated circuit (IC) manufacturer where packages are all made by the same subcontractor, it is reasonable to assume that the failure distribution statistics for temperature cycling would be very similar for all SOIC (small outline) packages with small dependence on the pinout (provided no unique features such as an internal heat sink is used). Where unique internal features or processes are involved, the statistics should be grouped by the unique process or package fabrication procedure.

Review of JPL data shows no failures for extended temperature cycling qualification testing. Review of PEM manufacturer test data shows rare failures (mostly at 1000 cycles) for the industry standard temperature cycling of −65 to +150 degrees Celsius (−55 to +125 degrees Celsius for larger packages). Mindful of this data, and if consistent with the data from the PEM manufacturer for the flight lot and similarly packaged parts, it is reasonable for a space project to accept more risk for this testing (e.g., reduce the test sample size).

5.0 PURE TIN LEAD COATING AND TIN WHISKER RISK MITIGATION DISCUSSION

The Restriction of Hazardous Substances (RoHS) initiative has meant that most commercial electronic devices will no longer be offered with lead as a major component of solder or lead termination. A minimum of 3% is needed to preclude growth of potential damaging tin whiskers in a space environment.

The most popular lead coatings for RoHS-compliant electronics are pure tin (including matte tin) and silver copper (which will also grow tin whiskers). Extensive research by NASA and others [5] has shown that acceptable risk mitigation is to dip the leads in ordinary (leaded eutectic) solder. However, this mitigation requires solder coating (dipping) to the body. The possibility of package cracking must be guarded against. The two methods are to either test on a sample (the DPA sample is convenient) or to perform PEM manufacturer (or package manufacturer, since this activity is usually subcontracted) testing.

Solder dipping is accomplished via IPC J-STD-2 followed by visual inspection for package cracking.

Therefore, unless the part manufacturer guarantees the PEMs to be qualified for space as having terminations containing at least 3% lead coating, these tests should be part of the qualification flow.

Another mitigation technique is to conformal coat the completed electronics boards containing the PEMs to be qualified. However, this technique is beyond the scope of this report.

6.0 ESTABLISHING A QUALIFICATION FLOW

1. Obtain history of PEM manufacturer test data, including burn-in or early-time life test data, life test data, extended temperature cycling data, process control or in-line fabrication test data that the manufacturer believes is relevant to the flight lot and is willing to send to the space system manufacturer.
2. Evaluate PEM manufacturer test data for relevancy to flight-lot risks for subject space application. In general, caution should be used and more manufacturer test data is required than would be generated on the real flight lot by the space system manufacturer.
3. Obtain approval of end item customer as to the assessments in 2.
4. Add to default qualification flow (life test, DPA, temperature cycling) any tests for risk mitigation of special problems such as inadequate life test monitor (increase sample size) and package risks (such as mixed epoxy mold compounds and mold compound darkening in optoelectronics devices).

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